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Preliminary Characterization of a Water Vaporizer for Resistojet Applications

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ABSTRACT

A series of tests was conducted to explore the characteristics of a water vaporizer intended for application to resistojet propulsion systems. The objectives of these tests were to (a) observe the effect of orientation with respect to gravity on vaporizer stability, (b) characterize vaporizer efficiency and outlet conditions over a range of flow rates, and (c) measure the thrust performance of a vaporizer/resistojet thruster assembly. A laboratory model of a forced-flow, once-through water vaporizer employing a porous heat exchange medium was built and characterized over a range of flow rates and power levels of interest for application to water resistojets. In a test during which the vaporizer was rotated about a horizontal axis normal to its own axis, the outlet temperature and mass flow rate through the vaporizer remained steady. Throttability to 30 percent of the maximum flow rate tested was demonstrated. The measured thermal efficiency of the vaporizer was near 0.9 for all tests. The water vaporizer was integrated with an engineering model multipropellant resistojet. Performance of the vaporizer/thruster assembly was measured over a narrow range of operating conditions. The maximum specific impulse measured was 234 s at a mass flow rate and specific power level (vaporizer and thruster combined) of 154×10^{-6} kg/s and 6.8 MJ/kg, respectively.

INTRODUCTION

Resistojet thrusters using water propellant have been baselined to perform a variety of low-thrust propulsion tasks during the past two decades. Biowaste resistojets, for which water was a candidate propellant, were baselined on the Manned Orbital Research Laboratory (MORL) in the early 1970's to provide orbit maintenance and control moment gyro desaturation.¹ In the late 1980's water resistojets were baselined to provide all propulsion for the Industrial Space Facility (ISF), a man-tended commercial platform originally scheduled for launch in the early 1990's.² Water resistojets were also considered for atmospheric drag cancellation on Space Station Freedom (SSF).

Water resistojets have some features which make them attractive

alternatives to more conventional propulsion systems. The benign nature of water makes for minimal logistical hazards, an important consideration for spacecraft intended to be refueled on orbit. Effluent from the shuttle orbiter fuel cells could be scavenged for use as propellant by shuttle-tended platforms, resulting in propellant launch cost savings. Recent analyses conducted by the Level II Space Station Freedom Program Office examined the potential benefit of water resistojet propulsion to SSF.³ These analyses assumed water propellant would be launched, with an associated reduction in hydrazine resupply requirements. The combined benefit of a favorable water propellant launch mass fraction and reduced hydrazine propulsion module ground processing costs was on the order of $\$10^8$ annually.

A water vaporizer employing a packed-bed heat exchanger was

designed, built and tested in support of the MORL program.⁴ Based on the limited data presented, it appeared to have operated stably over a narrow range of mass flow rates, and in various orientations with respect to gravity. Mass flow rates were controlled using a positive displacement pump or by feeding liquid from a pressurized reservoir. Heater power appears to have been manually controlled with the object of maintaining particular outlet temperatures. Although operation on a feed mixture of liquid water and gaseous carbon dioxide was reported to have been unsteady, thrust measurements made using only a liquid feed were steady. The results of the efforts described in Ref. 4 showed that a packed bed design could be suitable for resistojet applications, but some means of automatic power control would be required. The Ref. 4 concept was redesigned to process a higher flow rate, and an outlet temperature feedback proportional power controller was implemented.⁵ Results of the tests showed both steady and fluctuating outlet temperatures. Gravity sensitivity and outlet pressure data were not presented in Ref. 5.

A water resistojet which used vortical flow for phase separation was investigated in support of the ISF program.⁶ This device performed all vaporization and superheating using a single heater. A proportional-integral power controller with heater temperature feedback was employed⁷, and stable operation was demonstrated over a range of mass flow rates. Although the results presented in Refs. 6 and 7 indicated stable operation with the resistojet operating in a horizontal-axis orientation, subsequent tests showed a tendency for the system to go unstable after operation for approximately one hour. A version of the vortical-flow water resistojet was built and tested, and unpublished results showed considerable

sensitivity to orientation with respect to gravity. Operation in a vertical-axis orientation with liquid fed from the top produced the flow field predicted in Ref. 6, with a cylindrical liquid film surrounding a centrally-located heater/super-heater assembly. However, operation in a horizontal-axis orientation caused a liquid puddle to form in the bottom of the vaporizer. For that condition phase separation was due to gravity, not the radial acceleration of a swirling two-phase mixture.

The present work sought to build upon the experience base to demonstrate steady, repeatable operation of a resistojet water vaporizer over a range of mass flow rates and in a variety of orientations with respect to gravity. A vaporizer was designed which used a densely-packed porous heat exchange medium for the entire vaporization process. A power control scheme was devised which assured complete vaporization of the water over a range of mass flow rates. The sensitivity of this design to gravity was characterized using a rotisserie which enabled rotation of the operating vaporizer about a horizontal axis normal to the vaporizer axis. Thermal efficiency and outlet conditions were measured over a range of mass flow rates of interest for application to SSF. This same vaporizer was integrated with an engineering model multipropellant resistojet, and the performance of this assembly was measured at several operating conditions.

APPARATUS AND PROCEDURES

Vaporizer

The vaporizer was of the forced-flow once-through type (see Figure 1 for a sectional view) comprising a centrally-located cartridge-type heater and an outer densely-packed heat exchanger bed. The components and materials used were chosen to

enable demonstration of the vaporizer design concept in a timely manner, and not because they were necessarily optimum for this application.

The heater was a commercially-available unit, with a nickel-chromium alloy heating element and integral chromel-alumel (type K) thermocouple in the center. The inconel sheath was 15.7 mm in diameter by 108 mm long. This component was rated for 750 W at 120 Vac, with a maximum sheath operating temperature of about 1100 K recommended by the vendor. For application to the water vaporizer, the heater was operated on dc at a maximum of 150 V.

The heat exchanger was packed with granular silica (sand) with a maximum grain size of approximately 0.8 mm. Sand was chosen for the bed packing because it was likely to minimize the sensitivity of the two-phase flow field to gravity. In a simple experiment a column of sand 5 cm in diameter drew more than 200 cm³ liquid from a reservoir at its base to the maximum column height of 13 cm, leaving no liquid in the reservoir. This demonstrated a dominance of capillary effects over gravity in a sand-packed bed. The particular grade of sand used was not optimized, but was chosen based on availability.

The heat exchanger was a length of copper tubing, 81 cm long and 0.64 cm o.d., with a wall thickness of 0.8 mm. The sand was contained at the outlet by a sintered metal filter disk, and at the inlet by a commercially-available liquid flow resistor. The heat exchanger was formed by filling the straight copper tube with sand, then bending the tube into a helix on a 14.3 mm diameter mandrel. This ensured that the heat exchanger would fit snugly over the heater sheath, enhancing heat transfer between these components.

During operation, room temperature water was fed to the vaporizer from a pressurized

reservoir. The mass flow rate through the system was varied by changing the liquid feed pressure. The liquid flowed through the flow resistor, wherein a substantial pressure drop occurred. The liquid then proceeded into the packed bed, where heat was added to vaporize the liquid. The water vapor thus produced passed through the outlet filter and exited the vaporizer.

Thruster

The thruster was an engineering model multipropellant resistojet designed and fabricated for the NASA Lewis Research Center under contract to Rocketdyne and Technion. This thruster (see photo, Fig. 2) has been described in detail elsewhere.^{8,9} Briefly, all thruster components in contact with the flowing propellant were fabricated from grain-stabilized platinum, chosen for its long-term, high-temperature compatibility with a wide variety of oxidizing and reducing fluids. A centrally-located heat exchanger was overwound by a coiled sheathed heater with a platinum-10% rhodium alloy heater element, magnesium oxide insulator, and pure platinum sheath. An inconel shroud contained the heater, heat exchanger, and a radiation shield pack to reduce heat loss. This thruster was designed with a life goal of 10,000 h at a maximum temperature and internal pressure of 1670 K and 310 kPa, respectively. Maximum design power input was 500 W.

Facility

All tests were conducted in a rectangular vacuum tank measuring 2.1 m long by 0.9 m high by 1.7 m tall. This tank was equipped with a lobe-type blower backed by two rotary piston mechanical pumps, a system which was capable of maintaining test cell pressures at about 25 Pa with 175×10^{-6} kg/s of

water vapor flowing into the vacuum environment. For operation on water propellant, the main pumping system was augmented by a simple liquid nitrogen (LN₂) cryopumping system. This consisted of a 15-m length of 1.3-cm o.d. copper tubing formed into a helical cone and mounted at the inlet to the blower. A 0.1 m³ dewar was pressurized to about 0.13 MPa (absolute) to drive the LN₂ through the system. The gaseous nitrogen exhaust was discharged outside the laboratory to atmospheric pressure. Application of this system in parallel with the mechanical pumping train provided constant test cell pressures of about 0.05 Pa (measured using an ionization gauge) over the range of mass flow rates tested. The effects of test cell pressure on measured performance of low thrust rockets have been shown to be negligible at ambient pressures below about 0.13 Pa.¹⁰ Consumption of LN₂ was on the order of 15 kg/h.

Distilled water was used for all tests, and was fed to the vaporizer from a reservoir pressurized with nitrogen gas (see Fig. 3a). The pressure in the reservoir (P_f in Fig. 3a) was measured using a strain-gauge type pressure transducer with a range of 0 to 21 MPa. The mass flow rate through the vaporizer was varied by changing the feed pressure in the water reservoir. Propellant mass flow rate was measured using a Coriolis-effect mass flow meter. This unit had a range of 0 to 760×10^{-6} kg/s, and was calibrated by the factory on water. Spot checks of flow measured by the Coriolis-effect flow meter in series with a graduated sight glass showed agreement to be better than 1 percent. A solenoid-operated valve immediately upstream of the vaporizer enabled and disabled flow through the system (see Figs. 3b and 3c).

Power was provided to the vaporizer and thruster heaters by laboratory dc power supplies capable

of delivering 150 V at 12 A and 40 V at 25 A, respectively. Heater voltages were measured at the respective lead terminations. This was particularly important for measurement of the thruster voltage because the low heater resistance (ranging from 0.33 to 1.0 Ω) was of the same order of magnitude as the power leads between the power supply and thruster heater leads. Heater currents were measured using calibrated shunt resistors.

All data were measured, reduced, stored, and displayed using a microcomputer-based data acquisition and control system (DACS). The DACS also controlled a bank of relays, one of which switched power to the solenoid-operated shut-off valve at the vaporizer inlet. Two variable dc outputs from the DACS were used to modulate the outputs of the vaporizer and thruster power supplies during operation.

Vaporizer Tests

A series of tests was conducted to characterize vaporizer operation alone. The purposes of these tests were to quantify (a) the effects of orientation with respect to gravity on the operation of the water vaporizer, and (b) the thermal efficiency of the vaporizer over a range of operating conditions. During this series of tests the vaporizer was mounted on a rotisserie which enabled rotation of the operating vaporizer about a horizontal axis which was normal to the vaporizer heater axis. The rotisserie was operated by a geared synchronous instrument motor at a speed of one revolution per minute.

Operational parameters monitored during the gravity sensitivity and thermal efficiency tests included heater voltage and current, water feed pressure and mass flow rate, vaporizer heater temperature, two vaporizer mounting bracket temperatures, liquid inlet

temperature, vapor outlet temperature and pressure, and test cell pressure. The inlet temperature (T_i in Fig. 3b) was measured using a 1.6 mm diameter sheathed type K thermocouple probe inserted in the liquid feed line. Outlet temperature and pressure (T_o and P_o , respectively, in Fig. 3b) were measured in a small plenum downstream of the vaporizer. The junction of a 1.6 mm diameter type K thermocouple probe was located in the center of the plenum. A 30-cm length of 1.6 mm diameter tubing connected the plenum to the outlet pressure transducer providing a thermal stand-off between these components. This was necessary to avoid damage to the strain-gauge type pressure transducer (0 to 2.41 MPa), which had a compensation temperature limit of about 350 K. The hot vapor exited the plenum to the vacuum chamber through a 0.74-mm-diameter orifice.

Vaporizer heater power was controlled during all tests by modulating the output voltage of the vaporizer power supply. The power supply output was controlled by a variable dc output from the DACS to the remote control circuitry in the power supply which was proportional to the required heater voltage. The vaporizer was operated in preheat and vaporize modes. In the preheat mode the heater power was modulated to maintain a user-specified heater temperature (T_h in Figs. 3b and 3c) with no flow through the vaporizer. The DACS compared the measured heater temperature to the setpoint, then commanded the power supply to output a voltage at which power was proportional to the difference between the setpoint and the measured temperature. Full power was applied at temperatures more than 100 K below the setpoint; power was zero at or above the setpoint. In the vaporize mode the DACS controlled power to maintain specific power (i.e., the ratio of power

to mass flow rate) at a user-specified setpoint. This method of power control was chosen to assure that the power supplied to the heater was sufficient to completely vaporize all incoming liquid at any flow rate within the range of interest. The mass flow rate measured by the DACS was multiplied by the specific power setpoint to determine the necessary heater power. The voltage required for this power level was calculated based on the instantaneous heater resistance. The choice of constant specific power control was based upon the assumption that the power transferred to the water was linear with heater input power. Given the relatively high efficiency of this type of device, for which losses are small and vary little over the operating range, this was a reasonable assumption.

A test to investigate the sensitivity of the vaporizer to gravity effects comprised a 2.5 h operating session at a single setpoint (feed pressure and specific power) during which the vaporizer was rotated about a horizontal axis normal to its own axis. The rationale for this test was the suggestion that a lack of sensitivity to orientation with respect to gravity equated to a lack of sensitivity to the presence of gravity (i.e., low- or zero-gravity compatibility). The vaporizer was preheated to a heater temperature of 570 K for 30 min. The vaporizer was in a vertical-axis orientation with the liquid inlet at the top (vertical-downflow). Flow was initiated with a specific power setpoint of 3.0 MJ/kg and feed pressure set to about 3.8 MPa. The vaporizer was operated for 30 min in each of three orientations - vertical-downflow, horizontal, and vertical-upflow - before being returned to the vertical downflow orientation for a final 30 min of operation.

Tests to quantify the thermal efficiency of the water vaporizer over a range of operating conditions were

conducted with the vaporizer in the vertical-downflow orientation. These tests were conducted in one orientation only because insensitivity to gravity had been demonstrated earlier. The thermal efficiency was defined as the ratio of increase in water enthalpy to the specific power input. Values for the inlet and outlet water enthalpies were obtained from standard tables of steam properties¹¹, and were defined by the inlet temperature and outlet temperature and pressure. Conductive losses were estimated from two mounting bracket temperature measurements (conductive losses other than through the bracket were neglected based on the small cross-sectional areas available for heat transfer). Prior to flow initiation the heater was preheated to 570 K for 1 h. Data were obtained for steady operation at feed pressures of 1.1, 1.4, 2.1, 2.9, 3.5, and 3.8 MPa and the specific power was regulated at 3.0 MJ/kg for all tests. This specific power level was chosen to assure complete vaporization of the liquid without exceeding heater material temperature limits.

Vaporizer/Thruster Tests

A series of tests was conducted to investigate the characteristics of the water vaporizer when integrated with a resistojet. For these tests the vaporizer was removed from the rotisserie so that it could be mounted on a thrust stand, close-coupled to the resistojet (see Fig. 3c). To simplify the apparatus, the plenum, temperature probe, pressure tap, and orifice were removed from the vaporizer outlet.

Operational parameters monitored during the vaporizer/thruster assembly characterizations included vaporizer and thruster heater voltages and currents, water feed pressure and mass flow rate, thrust, vaporizer heater temperature, thruster nozzle temperature, and test cell pressure. Thrust was measured

using a calibrated displacement type thrust stand designed and fabricated at the NASA Lewis Research Center¹². This thrust stand was configured for full-scale displacement (approximately 5 mm) under an applied thrust of about 650 mN. The uncertainty of thrust measurements was 1 percent based on in-situ calibrations of the thrust stand under vacuum conditions. The temperature of the resistojet nozzle was measured using a two-color optical pyrometer focussed on the throat.

Thruster heater power was controlled in the same manner as the vaporizer heater power (see description above) with preheat and superheat control modes. The thruster preheat mode controlled heater power to maintain a set heater resistance, used as an indication of the average heater temperature. The superheat mode controlled power to maintain a constant specific power level.

Thruster performance tests began with a calibration of the thrust stand, following which the vaporizer and thruster were preheated for about 30 min. Performance was measured with vaporizer and thruster specific power levels each regulated to 3.0 MJ/kg for feed pressures of 3.7, 3.1, 2.9, and 2.7 MPa. Data were recorded when steady state was achieved, defined as stable operation with the rate of change in thruster nozzle temperature less than 1 K/min. Performance was also measured at a feed pressure and vaporizer specific power level of 3.8 MPa and 3.0 MJ/kg, respectively, but at a higher thruster specific power level of 3.8 MJ/kg. This was an attempt to measure the thruster's maximum performance capability. However, the power supply current capacity was inadequate to bring the thruster to its maximum operating temperature at the flow rates tested. Upon completion of the test series, flow and power were shut down to allow the thrust stand to re-establish a zero reading. Thrust stand zero drift

was always less than 0.5 percent of nominal thrust levels measured.

RESULTS AND DISCUSSION

Vaporizer Tests

Figure 4 shows the histories of vaporizer outlet pressure and temperature and mass flow rate over a two-hour period during which the orientation of the vaporizer with respect to gravity was varied. The arrows in Fig. 4 indicate the direction of flow through the vaporizer. At start-up, the vaporizer axis was vertical, with flow proceeding downward through the heat exchanger. Within 10 min the outlet temperature and pressure were within 90 and 98 percent of steady state values of 468 K and 380 kPa, respectively. The flow rate reached a steady state value of 170×10^{-6} kg/s within about 4 min.

The transients shown in the first 30-minute segment of Fig. 4 were characteristic of many starts conducted during the test program. Upon flow initiation an inrush of liquid into the heat exchanger was necessary to build up the liquid inventory. Outlet pressure increased gradually, causing a smooth reduction in flow rate until equilibrium was reached. Outlet temperature histories were similarly smooth.

After 30 min of operation in the vertical axis-downflow position the vaporizer was rotated 90° to a horizontal-axis position. Within 1 min of the rotation the outlet pressure fell by about 6 kPa, or about 1.5 percent of the nominal pressure. Outlet temperature and mass flow rate showed no response. After 30 min of operation in the horizontal-axis orientation the vaporizer was rotated another 90° to a vertical-axis orientation with flow progressing upward through the heat exchanger. A slight increase in outlet pressure accompanied this rotation. Again, no

outlet temperature or flow rate changes were observed. After another 30 min the vaporizer was returned to its original orientation. This time no changes in the outlet pressure were observed. At the end of 2 h of operation (30 min in each orientation) the vaporizer was shut down. Outlet pressure typically took about 5 min to return to zero following shutdown. This time was necessary to completely vaporize all liquid present in the vaporizer when the shut-off valve was closed.

The Fig. 4 data show that the vaporizer reached near-steady state conditions within 10 min of start-up. Operation was smooth and steady for the duration of the test, regardless of the orientation of the vaporizer with respect to gravity. This result clearly demonstrates a lack of sensitivity to orientation with respect to gravity. Therefore, it is likely that the vaporizer tested would be insensitive to the absence of gravity, and that the behavior observed in these ground-based tests was representative of that which could be expected on orbit.

Figure 5 shows the variation of outlet pressure and temperature with mass flow rate at a specific power level of 3.0 MJ/kg (recall that these values were measured in a plenum at the vaporizer outlet, just upstream of a 0.74 mm diameter orifice). Inlet temperature ranged from 293 to 295 K for all tests. The linear increase in outlet pressure with flow rate was expected. The asymptotic behavior of the outlet temperature at constant specific power indicates an increase in thermal efficiency with flow rate. Indeed, Fig. 6 shows that thermal efficiency at constant specific power increased from 0.886 at 53×10^{-6} kg/s to 0.914 at 173×10^{-6} kg/s, with associated thermal losses of 18 W to 45 W, respectively. Estimated conduction losses through the vaporizer mounting bracket ranged from 7 to 11 W, and increased with mass flow rate. Combined radiative and convective losses ranged from 11

to 34 W, also increasing with flow rate. The vaporizer performance test results are summarized in Table I.

An attempt to start at a feed pressure of 0.7 MPa resulted in an unstable condition, with mass flow rate and outlet pressure fluctuating sinusoidally, 180° out of phase. The period of oscillation was on the order of 30 s. This instability could have been caused by incompatibilities between the volumes of the packed bed heat exchanger and the outlet plenum, or between the pressure drop characteristics of the packed bed and the fluid resistor at the vaporizer inlet. Additional tests will be required to identify the critical relationships.

The variations of pressure drop through the fluid resistor and vaporizer with mass flow rate are shown in Fig. 7. Values for both parameters were calculated based on the measured mass flow rate and feed and outlet pressures. The fluid resistor pressure drop was calibrated versus flow rate prior to vaporizer assembly. The resulting relationship was:

$$\Delta P_{\text{res}} = 2.77 \times 10^7 \dot{m}^2$$

where ΔP_{res} and \dot{m} were the fluid resistor pressure drop in MPa and mass flow rate in kg/s, respectively. The vaporizer pressure drop was then estimated by:

$$\Delta P_{\text{vap}} = (P_i - P_o) - \Delta P_{\text{res}}$$

where P_i and P_o are the inlet and outlet pressures, respectively, shown in Figs. 3a and 3b. The ratio of the pressure drop across the vaporizer to that for the fluid resistor ranged from about 3 at the highest flow rate tested to about 8 at the lowest flow rate. This indicates that the vaporizer pressure drop characteristics had an increasingly dominant effect on mass flow rate with decreasing flow rate. Thus pressure fluctuations within the vaporizer were more likely to

propagate upstream through the feed system, leading to flow instabilities at low flow rates. To avoid this situation, the vaporizer-to-fluid resistor pressure drop ratio must be decreased so that the fluid resistor will dominate the system pressure drop characteristics. The most appropriate range of values for this ratio must be determined experimentally.

Vaporizer/Thruster Tests.

Figure 8 summarizes the performance data measured for the vaporizer/thruster assembly. At constant vaporizer and thruster specific power levels of 3.0 MJ/kg each the specific impulse increased with mass flow rate over the range tested. This was expected, based on (a) the observed increase in vaporizer efficiency with mass flow rate (see Fig. 5), and (b) the well-known improvement in resistojet nozzle efficiency with throat Reynold's number¹³. Specific impulse increased as the thruster specific power was increased to about 3.8 MJ/kg while the vaporizer specific power was held constant at 3.0 MJ/kg. The maximum measured specific impulse of 234 s was obtained with the thruster power supply operating at its current limit. The thruster temperature design limit had not been reached; higher specific impulse values could likely have been measured using a higher-capacity power supply. Results of the vaporizer/thruster performance tests are summarized in Table II.

Stable operation at feed pressures below 2.9 MPa were difficult to achieve. The instabilities observed were similar to those encountered during operation of the vaporizer alone, although the onset of instability occurred at a higher feed pressure and mass flow rate for the vaporizer/thruster assembly. In addition, the period of oscillation increased to about 120 s.

SUMMARY AND CONCLUSIONS

An existing vacuum chamber was modified to facilitate tests of a resistojet water vaporizer and thruster. Modifications included the installation of a simple, inexpensive LN_2 cryopumping system. The target had a total surface area of approximately 0.6 m^2 , and LN_2 consumption was on the order of 15 kg/h. The cryopump provided sufficient augmentation of the test cell's mechanical pumping train to reduce test cell pressure during vaporizer operation from about 21 Pa to less than 0.01 Pa.

A laboratory model of a forced-flow, once-through water vaporizer employing a porous heat exchange medium was built and characterized over a range of flow rates and power levels of interest for application to water resistojets. In a test during which the vaporizer was rotated about a horizontal axis normal to its own axis, the outlet temperature and mass flow rate through the vaporizer remained steady. Small changes in outlet pressure were observed which were not explained; they were not believed to be an issue with respect to resistojet applications of the vaporizer concept tested. The insensitivity of this design to orientation with respect to gravity suggest compatibility with a low-gravity environment on orbit.

The thermal efficiency of the vaporizer ranged from 0.886 to 0.914, and increased with mass flow rate at constant specific power. Significant increases in efficiency should be attainable with design optimization. Throttability to 30 percent of the maximum flow rate tested was demonstrated. Vaporizer operation became unstable at very low flow rates. This instability could have been caused by incompatibilities between the pressure drop characteristics of the packed bed and the fluid resistor at the vaporizer inlet. Additional tests

will be required to identify the critical relationships.

The water vaporizer was integrated with an engineering model multipropellant resistojet. Performance of the vaporizer/thruster assembly was measured over a narrow range of operating conditions. The maximum specific impulse measured was 234 s at a mass flow rate and specific power level (vaporizer and thruster combined) of $154 \times 10^{-6} \text{ kg/s}$ and 6.8 MJ/kg, respectively. Performance was limited by the capacity of the thruster power supply; the thruster material temperature limit was not reached. Further tests are required to define water resistojet performance limits.

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Table I. Vaporizer Characteristics Summary

Vaporizer Voltage, V	55.0	63.3	76.0	87.7	95.8	99.5
Vaporizer Current, A	2.90	3.35	4.05	4.66	5.09	5.27
Vaporizer Power, W	159	212	308	408	487	525
Mass Flow Rate x 10 ⁶ , kg/s	53.2	70.8	103	136	162	174
Specific Power, MJ/kg	3.00	3.00	3.00	3.01	3.01	3.01
Feed Pressure, MPa	1.05	1.45	2.10	2.87	3.53	3.86
Outlet Pressure, kPa	119	158	224	296	352	380
Inlet Temperature, K	295	294	294	294	293	294
Outlet Temperature, K	412	429	446	453	458	462
Vaporizer Heater Temperature, K	812	862	920	961	988	1000
Efficiency	0.886	0.899	0.908	0.912	0.916	0.916

Table II. Vaporizer/Thruster Assembly Characteristics Summary

Vaporizer Voltage, V	98.2	90.1	86.2	83.2	92.6
Vaporizer Current, A	5.24	4.82	4.60	4.44	4.97
Vaporizer Power, W	515	434	397	369	460
Thruster Voltage, V	20.5	18.7	17.9	17.2	22.5
Thruster Current, A	25.1	23.1	22.3	21.6	25.9
Thruster Power, W	515	432	399	372	583
Total Power, W	1029	866	796	741	1043
Mass Flow Rate x 10 ⁶ , kg/s	171	144	132	122	152
Vaporizer Specific Power, MJ/kg	3.01	3.01	3.01	3.02	3.03
Thruster Specific Power, MJ/kg	3.01	3.00	3.02	3.05	3.84
Total Specific Power, MJ/kg	6.02	6.02	6.03	6.07	6.86
Feed Pressure, MPa	3.70	3.13	2.87	2.70	3.84
Thrust, mN	372	310	278	257	349
Specific Impulse, s	222	219	215	215	234
Vaporizer Heater Temperature, K	1071	1048	1038	1026	1051
Thruster Nozzle Temperature, K	1397	1374	1350	1330	1510

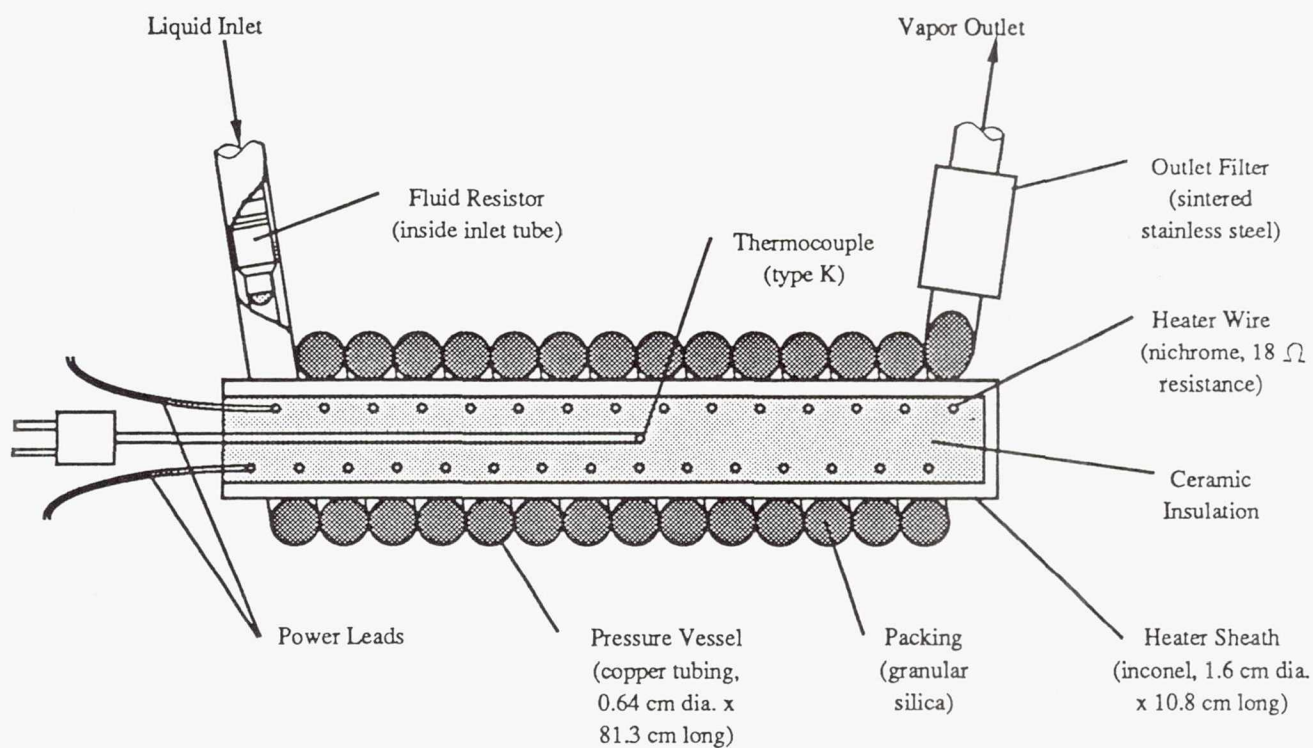


Figure 1. Laboratory Model Water Vaporizer (axial section)

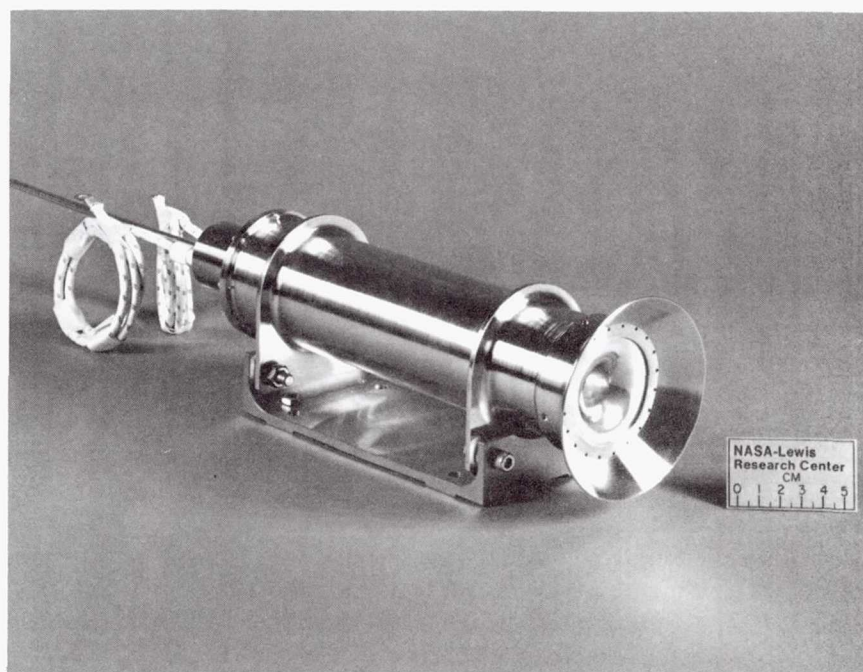
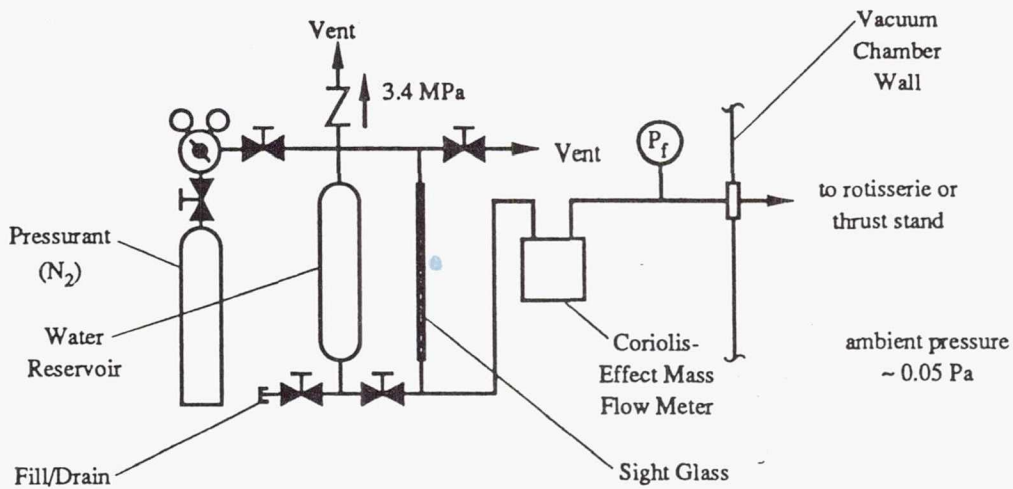
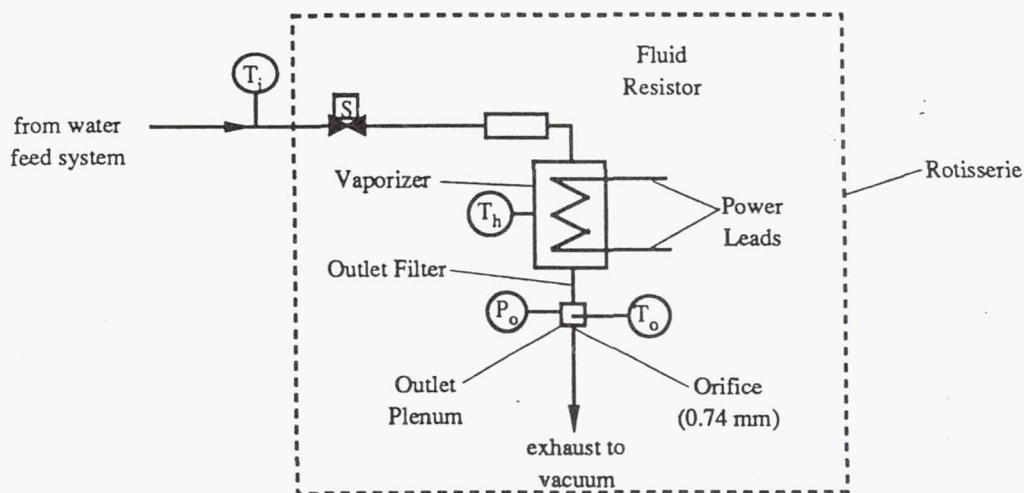


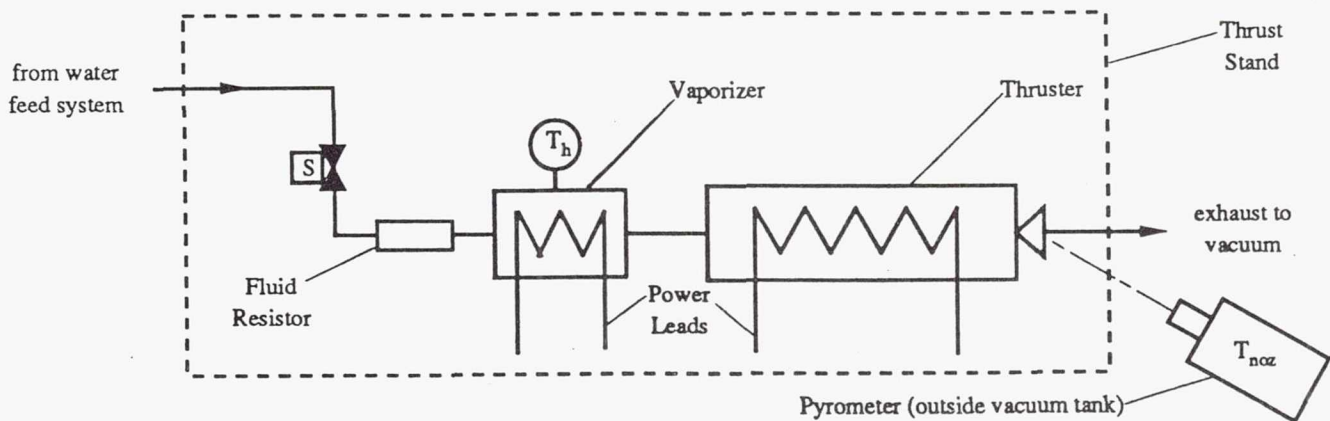
Figure 2. Engineering Model Multipropellant Resistojet



(a) Water Feed System



(b) Water Vaporizer on Rotisserie (inside vacuum chamber)



(c) Vaporizer/Thruster Assembly on Thrust Stand (inside vacuum chamber)

Figure 3. Water Vaporizer and Vaporizer/Thruster Assembly Characterization Apparatus

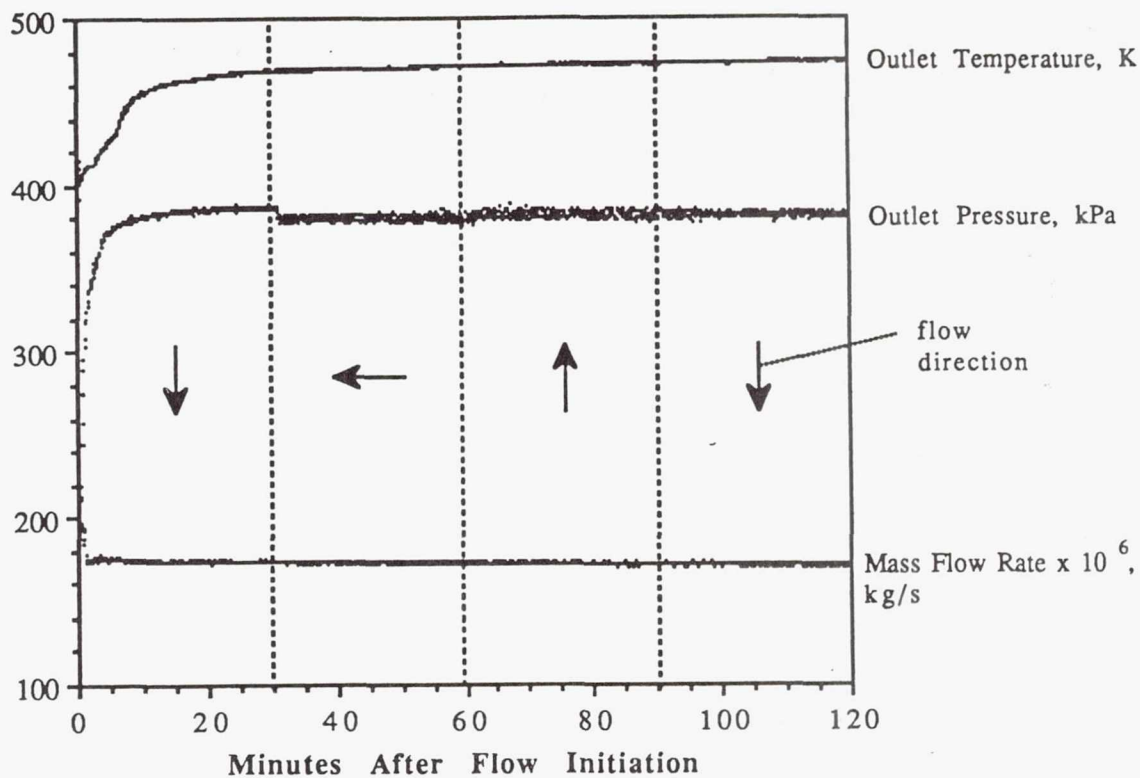


Figure 4. Water Vaporizer Gravity Sensitivity
(Feed Pressure = 3.7 MPa; Specific Power = 3.0 MJ/kg)

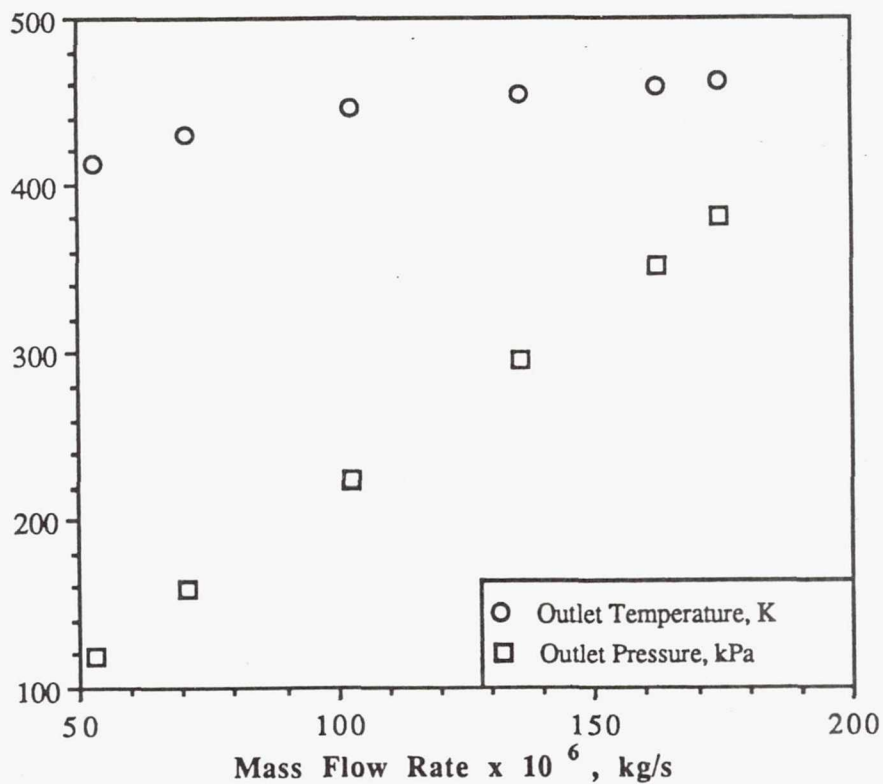


Figure 5. Water Vaporizer Outlet Conditions
(Specific Power = 3.0 MJ/kg)

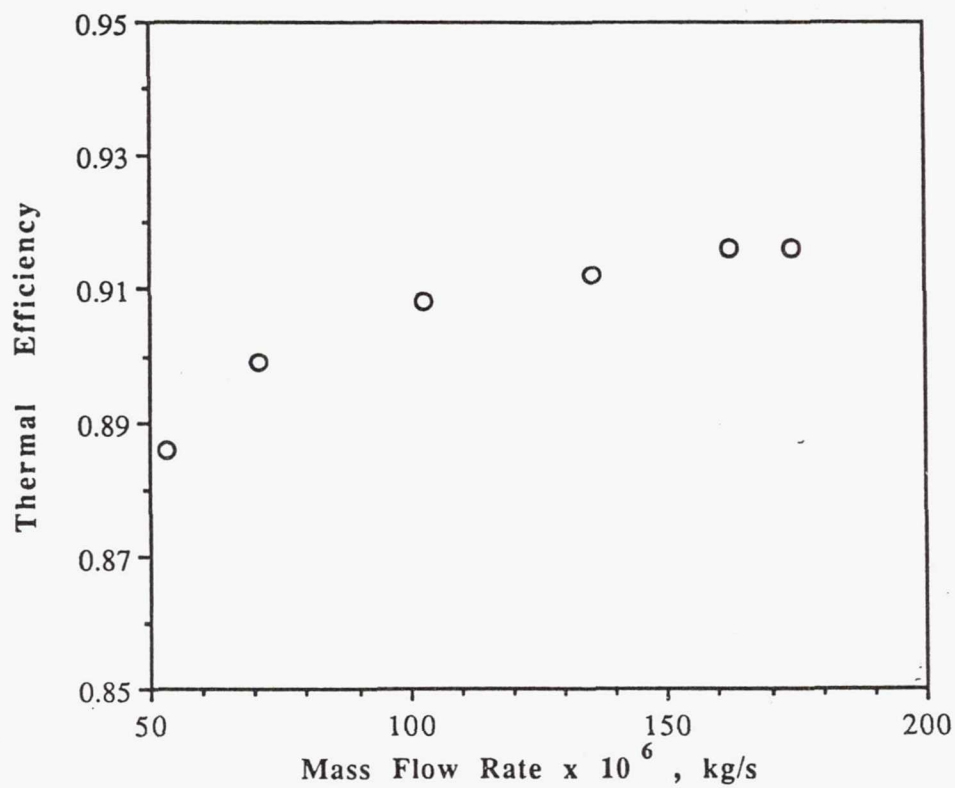


Figure 6. Water Vaporizer Efficiency
(Specific Power = 3.0 MJ/kg)

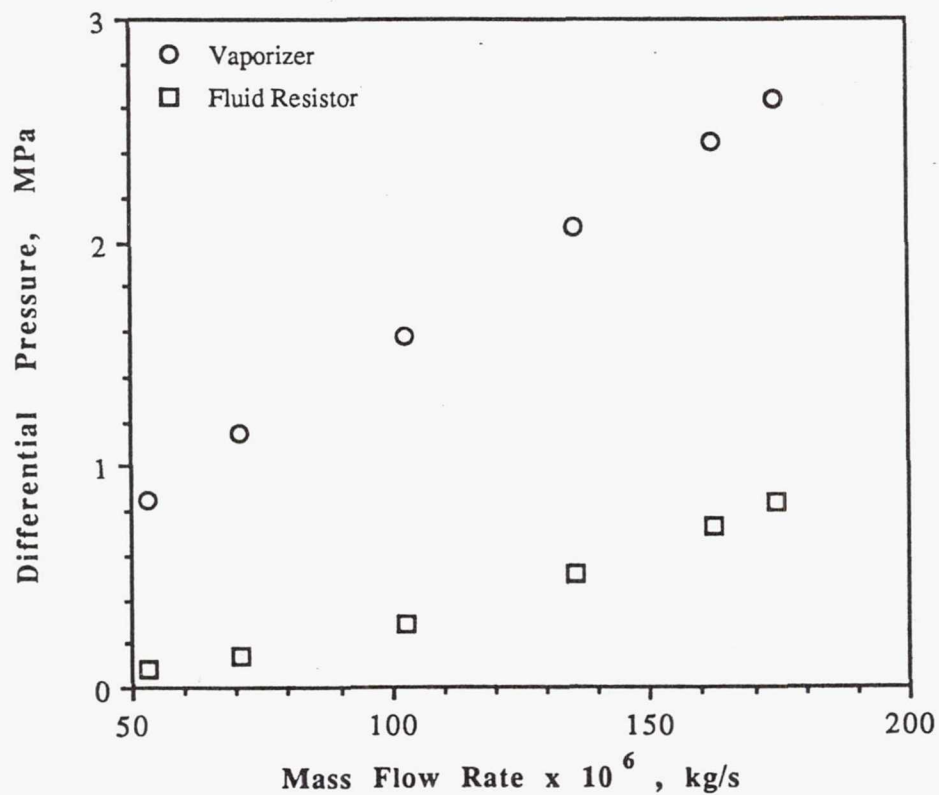


Figure 7. Water Vaporizer and Fluid
Resistor Pressure Drop Characteristics

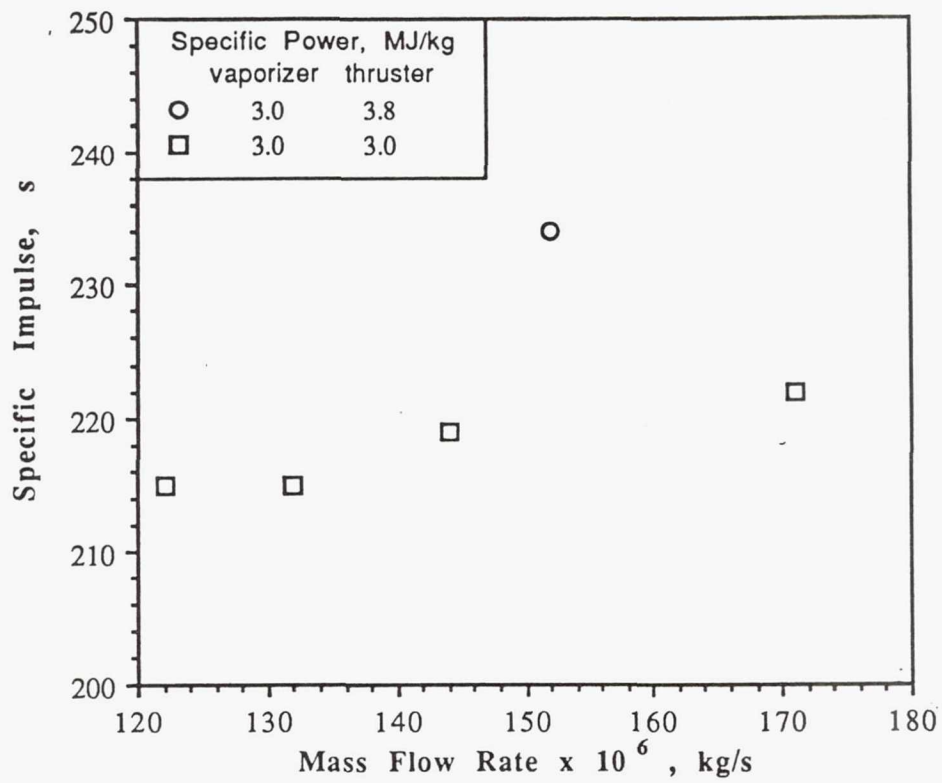


Figure 8. Water Vaporizer/Resistojet Assembly Performance

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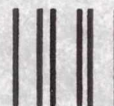
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